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Behavior of the Lean Methane-Air Flame at Zero-Gravity

by

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A special rig has been designed and constructed to be used with the NASA Lewis Research Center Airborne Research Laboratory to study the effect of gravity on the behavior of lean fuel-air flames in a standard (one end closed) 50.4 mm. (2") internal diameter tube when the mixtures are ignited at the open end. Design constraints are discussed and the procedure for using the rig is described. The propagation of lean methane-air flames over the range of 5.05 to 6.1 volume percent methane was studied. The lean limit at zero gravity was found to be 5.10% methane and the flame was found to extinguish as previously observed for downward propagating flames at one g. It was observed that g-jitter could be maintained at less than ± 0.04 g for most zero g trajectories. The flames were found to be sporadically cellularly unstable at zero g. The effects of g-jitter were studied. Upward propagation at two g yielded the expected stable flame cap propagation. When the g level was increased from zero g at ignition to one g downward during propagation of the flame, the flame extinguished at rather low g levels when the methane concentration was less than 5.86% CH_4 (the downward lean limit at one g) and did not extinguish at higher methane concentrations.

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Abstract

A special rig has been designed and constructed to be compatible with the NASA Lewis Research Center Airborne Research Laboratory to allow the study of the effect of gravity on the behavior of lean fuel-air flames near their lean limit in a standard 50.4 mm (2") internal diameter tube when the mixtures are ignited at the open end and propagate towards the closed end of the tube. Design constraints including safety constraints are discussed and the final design and the procedure for using the rig are described.

The rig was used to study the propagation of lean methane-air flames over the range of 5.05 to 6.1 volume percent methane. The lean limit at zero gravity was found to be 5.10% methane and the flame was found to extinguish in a manner previously observed for downward propagating flames at one g. It was observed that g-jitter could be maintained at less than ± 0.04 g on most zero g trajectories. All of the propagating lean limit flames were found to be sporadically cellularly unstable at zero g. There was no observable correlation between the occurence of g-jitter and the lean limit, average propagation speed of the flame through the tube or the occurrence of cellular instability. Some experiments on upward propagation at two g yielded the expected stable flame cap propagations up the tube with a longer skirt. In a few experiments in which the g level was increased from zero g at ignition to one g downward during propagation of the flame, the flame extinguished at rather low g levels when the methane concentration was less than 5.86% CH_4 (the downward lean limit at one g) and did not extinguish at higher methane concentrations.

I

INTRODUCTION

This study examined the behavior of the lean limit methane-air flame in a standard flammability limit tube (SFLT) at zero-g. Previously, a similar study had been performed in the 2.2 second drop tower at NASA Lewis Research Center (Strehlow and Reuss, 1980). This previous work was restricted, however, by a lack of sufficient time at zero-g. For flames of this type, propagation speeds are on the order of 10 cm/sec. Since the standard tube is approximately 1 meter to 1.5 meters in length, 2.2 seconds is not sufficient time in which to observe the entire flame history. Note that the propagation speed is the rate of propagation of the flame tip and not the burning velocity; these two quantities are equal only for flat flames. A new facility which is being used in this study, namely the NASA Lewis Research Center Learjet Airborne Research Laboratory, provides sustained zero-g for upwards of 20 seconds. This allows flames to be examined throughout their entire lifetime. This improvement is of utmost importance since the definition of a flammability limit requires that the near limit flame propagate the entire length of a standard flammability limit tube. Thus, this present study has enabled us to determine for the first time the lean limit, as defined by the U.S. Bureau of Mines (Coward and Jones, 1952), for methane at zero-g. In addition to determining the zero-g lean limit for this apparatus, other characteristics of the zero-g flame's behavior are also examined. These characteristics include flame speed and structure as a function of composition, and the method of extinction.

Besides zero-g flames, this study examines the behavior of flames in transitional gravity and the effect of small gravity fluctuations, or g-jitter, on flames. In the case of transitional gravity, flames have been observed during the transition from zero-g to sufficiently large positive gravity. Of some interest is the behavior of flames which are ignited in zero-g and propagate downward as gravity loading is applied. In the case of transitional gravity, flames have been observed during the transition from zero-g to sufficiently large positive gravity. Of some interest is the behavior of flames which are ignited in zero-g and propagate downward as gravity loading is applied. In the case of small gravity fluctuations, their effect on flame speed and shape is investigated. In both of these cases, mainly qualitative observations are reported because the data for these flames are not as extensive as in the zero-g case.

II

EXPERIMENTAL APPARATUS AND PROCEDURE

2.1 NASA Lewis' Learjet Facility

Research for this study was carried out at NASA Lewis Research Center's Airborne Research Laboratory in Cleveland, Ohio. This facility includes a Learjet Model 25 airplane which has been equipped specifically for research purposes. The original seating configuration has been changed to include seating for only three persons; this allows cabin space for the research apparatus (see Fig. 1). Electrical buses are available to the researcher and include AC and DC supplies at various voltages and power ratings. For more information on this facility the NASA Learjet Model 25 Airborne Research Laboratory Experimenter's Handbook (NASA, no date available) may be consulted.

The zero-g environment is obtained in the Lear Jet facility by flying along Keplerian trajectories. Transitional gravities are obtained by adjusting a part of this trajectory, and small gravity fluctuations are the inevitable result of imperfections in the trajectories caused by the minor disturbances of normal flight.

Due to the nature of this facility stringent safety requirements have to be met. In addition to conventional air safety requirements, zero-g gravity flight, as well as the use of combustibles, leads to additional requirements. Due to the absence of gravity all items on board have to be securely fastened to prevent floating objects which might impair the testing procedure, damage research equipment, or cause injury to the researchers. For this reason all electircal leads are secured through the use of cannon-plugs and all mechanical equipment is

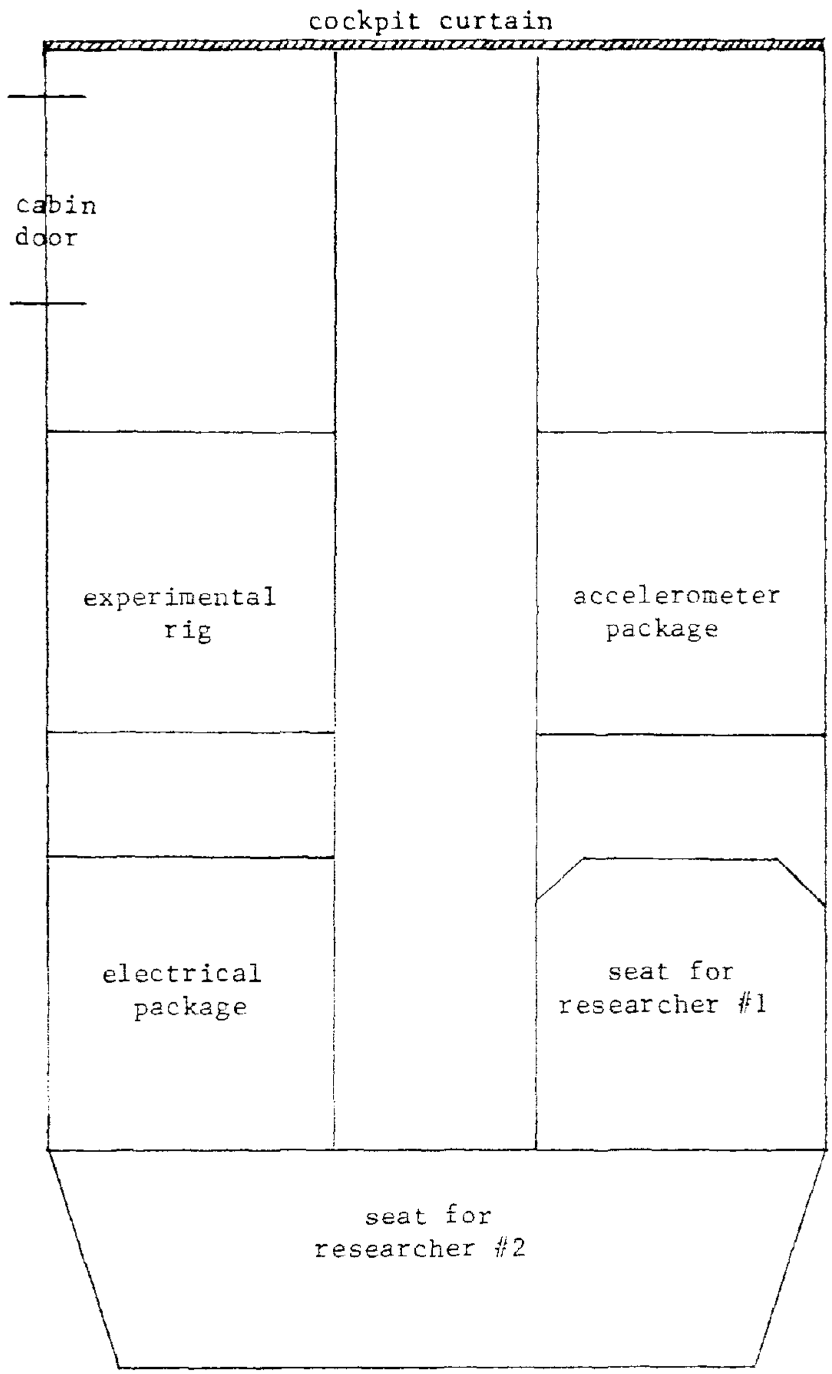

Fig. 1. Aircraft cabin layout.

either bolted or pinned in place. The researchers also have to be securely belted to their seats in order to avoid injury. Combustion safety requirements and how they were satisfied are discussed in Section 2.4.

In addition to requirements imposed by zero-g conditions, standards of structural integrity have to be complied with. These standards, which meet or exceed FAA standards for this type of aircraft, consist of load factors which must not produce yield stresses in the materials used, and construction specifications. The load factors which must not cause the materials to yield are as follows (NASA, no date available):

Load Direction	Load Factor
Forward	9.0g
Down	7.0g
Up	2.0g
Side	1.5g
Aft	1.5g

These requirements were established to insure the structural integrity of the installation. Note that these load requirements must also be met by all welds and bolted fastenings.

The construction specifications deal mostly with fitting the equipment into the experimental racks. These standardized racks were designed and built by NASA to allow for easy installation into the aircraft and the experimental apparatus must be designed to be fully contained in these racks. Another construction specification is that all fasteners have to be secured by self-locking nuts or safety wire.

2.2 The Experimental Rig

Along with the safety requirements, constraints due to available space and construction specifications and the difficulty of movement by the researchers in flight led to the design of a system which would be as self-sufficient as possible. It was also desirable to have a system which could be operated from a stationary, seated position, with few actual tasks to be performed by the researcher. With these factors in mind an automated system became essential. Additionally, the system had to be simple in order to allow adjustments to be made easily, and to allow fast and easy repair. To achieve this simplicity, a mechanically automated system was chosen instead of an electronically automated system. This automated system also required a suitable test apparatus.

In order to have a self-contained system it is necessary that a number of standard flammability limit tubes be filled before flight and ignited and filmed one by one during the required trajectories. To allow for the filming of these flames by a single set of stationary cameras, a carousel configuration for the tubes was designed. Eight tubes are placed along the perimeter of a circular metal plate which can be rotated with respect to the vertical axis, inside the experimental rack. The rotating plate can then be locked in place, in one of eight positions, insuring proper positioning for firing.

It is imperative for safety purposes that the mixtures in the filled tubes cannot be ignited accidentally, and to prevent the possibility of a tube shattering due to excess pressure, it is also required that ignition of a filled tube occurs only when one end is open. These factors necessitate ignition of a single tube, only when that tube is in its proper firing position with an open end, and only during a test run. Since the mixtures in the tubes are ignited electrically the system was designed to allow electrical contact only with the circuit of the tube in the firing (and filming) position.

To insure against igniting the mixture in a closed tube a second electrical safeguard is employed. While the tube in firing position is the tube which is supplied with current, the line carrying the current is connected to an open circuit which can only be closed when a microswitch is triggered. This microswitch is triggered when the microswitch arm makes contact with a sliding valve plate only when the valve plate is in the open position.

The sliding valve plate is pushed to its open position by a piston/pressure cylinder arrangement and pulled closed by a spring mechanism. This system allows the valve plate to be activated by an automated process rather than by the researcher. The piston/cylinder arrangement consists of a high-pressure air cylinder which releases pressurized air through an electrically controlled solenoid valve into the piston housing, actuating the piston. The piston in turn pushes the sliding valve to its open position. Through another port of the solenoid valve the pressurized air is exhausted, allowing the piston, and thus the sliding valve, to slide back into the closed position.

The tubes used in this study are modified versions of standard flammability limit tubes (SFLT's). The SFLT was defined by Coward and Jones (1952) as a two-inch inner diameter tube approximately four to six feet in length. This tube is open at one end (also the end at which ignition takes place) and closed at the other end.

There are eight SFLT's in the carousel arrangement (see Fig. 2). These tubes are approximately 28 inches in length - their length was

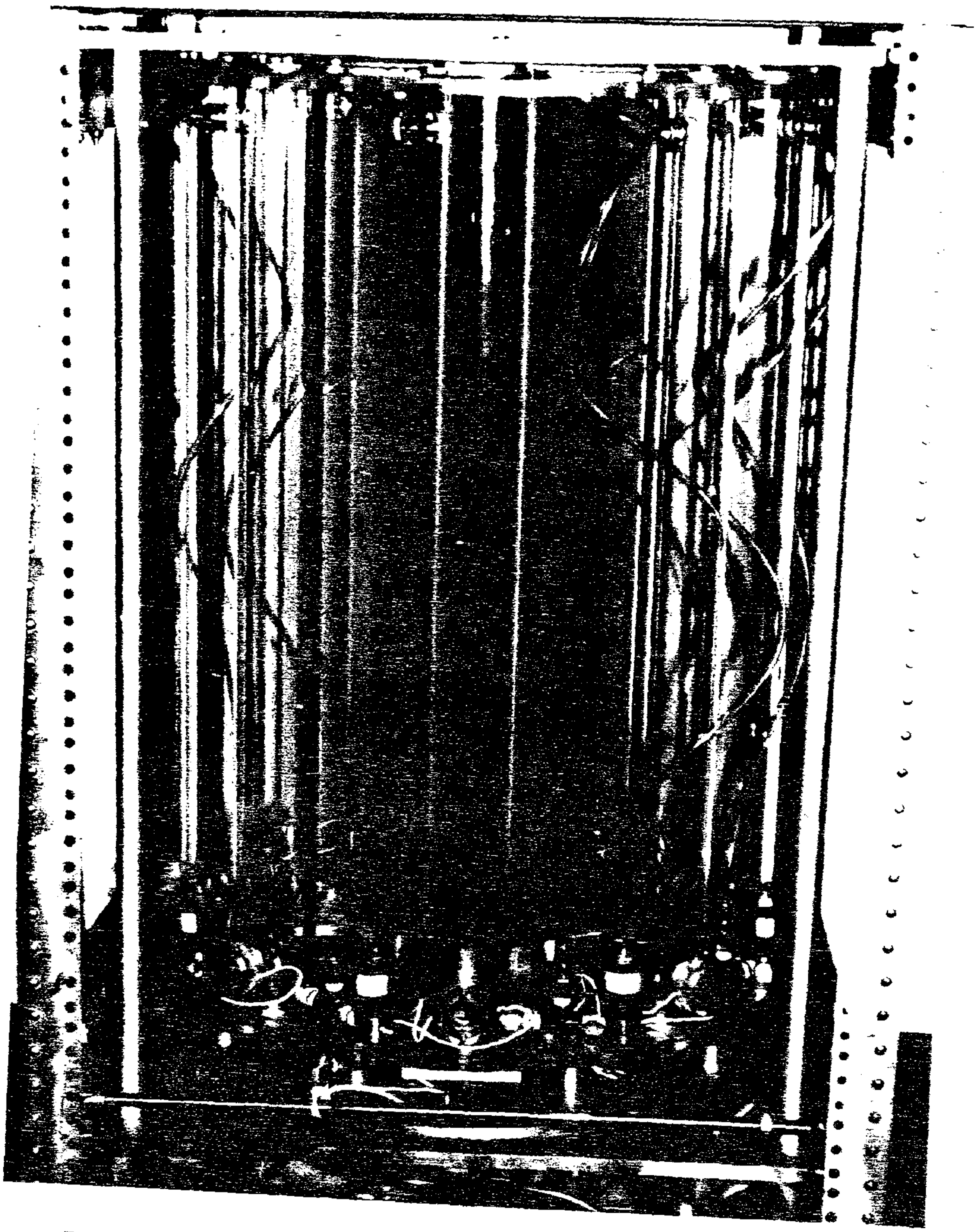

Fig. 2. Experimental rig (shown here with patch hoses).

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shortened to fit in the available space. They are made of standard clear plexiglass tubing which has sufficient optical quality to allow visual light photography of the flames. These tubes have the ignition source at the end which opens and an O-ring sealed, removable plexiglass cap at the other end. This removable cap facilitates cleaning of the tubes.

The ignition end of each of the tubes is modified to hold the removable igniters (see Fig. 3). A circular hole has been bored through the tube wall at this end. At this hole, the tube has attached to it a plexiglass collar, with a hole of the same diameter, which has been fused to the tube's outer wall. This collar is fitted with bolts which serve not only to hold the igniters in place but also to carry the current to the igniter coils. Another feature at the ignition end of the tubes is the inclusion of a pressure release valve which, when electrically triggered, opens the tube to the atmosphere. The reason for including this valve is to allow the pressure of the mixture in the tube to come to equilibrium with the cabin pressure. By opening this valve approximately one second prior to opening the tube for ignition, the pressures are equalized. This prevents sudden expulsion of mixture when the main sliding valve is opened. Such a late release of mixture causes flow inside the tube during the ignition process and disturbs flame propagation.

In order to insure ignition the nichrome coils are chemically treated. The coils are dipped in a solution of nitrocellulose and acetone and allowed to dry. When current is then passed through the coil, heating the coil, the nitrocellulose residue ignites in a small burst of flame providing ample energy to ignite the flammable mixtures. This insures that an ignition limit will not be observed in these experiments.

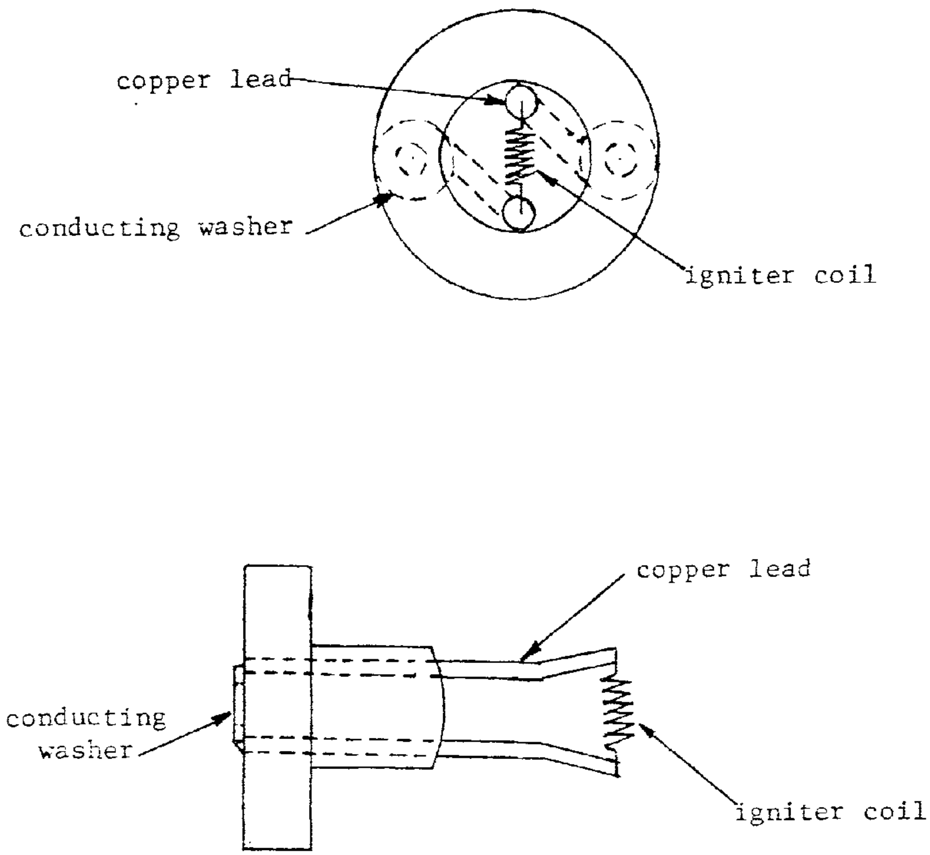

Fig. 3. A removable igniter (not to scale).

In addition to the tubes and their igniter systems, digital voltmeters, which receive as a signal the real-time output of three orthogonally positioned accelerometers, are an integral component of the experimental rig. In order to determine the effect of gravity on flames, continuous gravity readings are essential. Therefore, by placing these voltmeters, or g-meters, on the experimental rig in a position where they can be filmed, the gravity loads can be determined at any time during flame propagation. Along with the g-meters, a cabin pressure meter was placed on the experimental rig, allowing continuous pressure readings to be recorded.

2.3 Electronics and Automatic Sequencing

The electronics package used in this experiments serves two main purposes. It regulates the research power supplied by the aircraft for use in the experiment, and it controls the automatic sequencing. These two functions are quite interrelated since all but one of the experimental system's electrical components play a part in the automatic sequencing process. The electrical package also contains two 28V high speed cameras and a pressure condenser.

The cameras, focused on the tube in firing position in the experimental rig, are positioned one above the other so that one camera films the bottom two-thirds of the tube while the other camera films the top two-thirds of the tube. The area of overlap is the area of the rig in which the g-meters have been positioned, allowing both cameras to record real time gravity readings. The cameras run on a current of 2 A each (4 A total), with a starting current of 5 A each (10 A total). The pressure condenser measures the cabin pressure, and is wired to the digital pressure meter located on the experimental rig in the image plane.

The electrical power is supplied by the aircraft in both alternating and direct currents. This particular experimental configuration uses only the 10 A-28 V DC and the 10 A-115 V-60 Hz AC supplies. The current is carried from the aircraft's research power supply to the elctrical package through shielded wire with all connections made by cannon-plugs. Both the 28 V and 115 V lines are connected to a single pull-double throw master on/off switch. In this arrangement all system power may be shut down by throwing a single switch. From this switch, the 28 V line is passed through a 10 A fuse and the 115 V line is passed through a 1 A fuse. This prevents any possible power overloads to the system circuitry. After passing through the fuses the two lines are connected to their respective indicator lights. These lights indicate whether or not current is being supplied to the system by the 28V and 115 V lines.

From its indicator light the 28 V line is connected to the ignition circuit. This is the sole electrical component which is not directly controlled by the automatic sequencing system. This circuit includes a 38,000 microfarad capacitor in series with a 100 ohm, high power resistor which controls the flow of current to the capacitor. This combination has a charging time constant of about 15 seconds which is sufficient to insure that capacitor is fully charged prior to the firing of the next tube. The 38,000 microfarad capacitor was specifically chosen because its discharge was strong enough to always provide ignition, while not being so strong as to burn out the nichrome wire igniters. A DC voltmeter is patched across the leads of the capacitor to indicate whether or not the capacitor is fully charged. The leads of the capacitor are attached to shielded wire which connects by cannon-plug to the experimental rig. On the experimental rig the ignition circuit is completed as the lines from the two capacitor leads are connected to the two knife-switches. These knife-switches are wired to the leads of the igniter of the tube which is in firing position. Consequently, during ignition the capacitor is discharged through the circuit and thus through the igniter.

The automatic sequencing system consists of the timer box, sequencing on/off switch, and sequencing indicator light. The most important component of the automatic sequencing system is the timer box. The timer box contains a low-speed motor, its axle, and four aluminum disk/microswitch combinations attached to the axle. The low-speed (2 rpm) timer drive motor is fastened to the timer box, and the motor axle extends through the timer box. The motor axle passes through the centers of the aluminum disks which are then fastened to the axle by set screws. Therefore, the disks rotate at 2 rpm when the timer drive motor is running. These circular disks have been machined along their perimeters to contain raised and depressed regions. Microswitches have been fastened inside the timer box in such a way that the microswitch arms extend to the edges of the disks. In this way the raised regions will engage the microswitch arms and trigger the microswitches while the depressed regions will not. By machining the depressions to a fixed arc length along the perimeter of the disks, the microswitches can be engaged for a fixed time interval. Furthermore, by adjusting the angular position of these disks with respect to the motor axle the exact timing of the triggering of the microswitches can be controlled. The sequence in which the camera motors and other electrical components are activated is represented graphically in Figure 4.

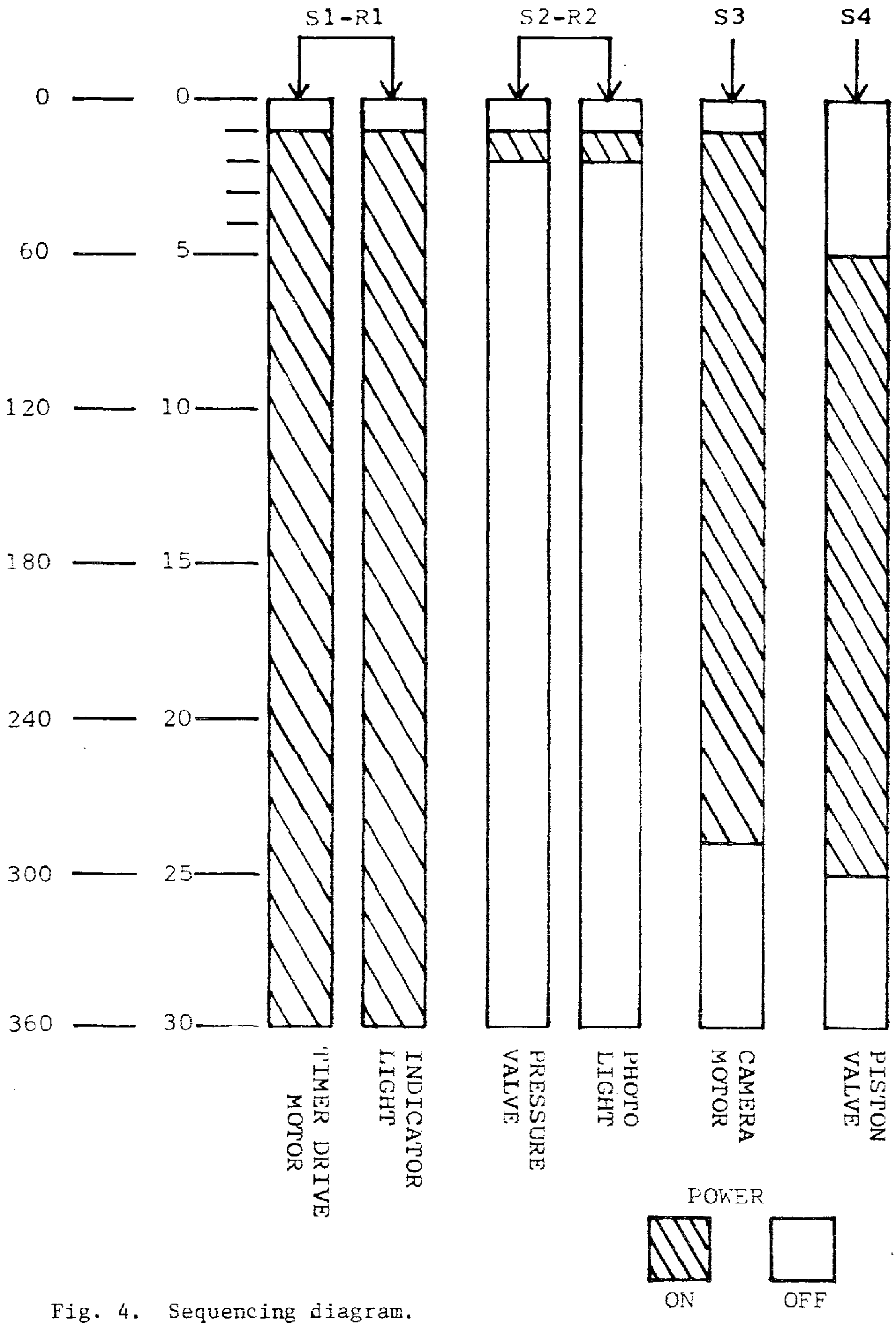

Fig. 4. Sequencing diagram.

2.4 Tube Filling Methods

Flame behavior as a function of mixed composition is perhaps the most important aspect of this study. Consequently, an accurate flow regulation and tube filling system is necessary. In addition, the use of flammable methane necessitates that care be taken in all steps of the filling process to insure safety.

The method employed to insure that the mixtures are lean is to test mixtures in the composition test tube. The composition test tube is a single, portable SFLT, identical to those used in the rig, which has its own ignition circuit and can thus be ignited on the ground. All mxtures used to fill the tubes in the experimental rig also fill the composition test tube which is then ignited on the ground. In this way a visual inspection of the behavior and tip velocity of the flame in the composition test tube is used to insure that the mixture that has been placed in the tubes in the rig has the desired composition. Carefully calibrated rotometers gauged the flows of the methane and air. These rotometers were calibrated under constant back pressure by measuring fluid displacement. Another safety consideration is that the filling is always done outside of the airplane and at a safe distance from any aircraft. Additionally, all exhaust gases are vented to the outside of the hangar in which the filling takes place.

All the tubes have two quick-disconnect valves fused into the tube walls, one near the top of the tube and one near the bottom of the tube. These quick-disconnect plug and socket connectors allow flow to pass through them only when properly engaged and sealed. The tubes can be filled by connecting the fill hose to the quick-disconnect socket at one end of the tube. The gas mixture flows from the fill hose into the tube at that end, and the gas which was in the tube is exhausted at the tube's other end through a similar quick-disconnect socket. In order that more than one tube may be filled with the same mixture, patch hoses with quick-disconnect plugs were constructed. These patch hoses can be used to patch two or more tubes together so that the exact same mixture fills all of them. The procedure is to choose the composition and the number of tubes to be filled with that mixture. Each of the tubes to be filled is then patched to the mixing chamber with the composition test tube connected last. The desired mixture is allowed to flow into the tubes for a period of time which causes the displacement of ten times the volume of the system to be filled. All hoses are standard 1/8 inch tygon tubing.

2.5 In Flight Procedure

The aircraft cabin is arranged so that system components are visible to, and within easy reach of the researcher. The researcher is seated alongside the test rig, close enough so that any manipulation or adjusting of the rig may be performed. The electrical rack, including cameras, is installed and fastened at a fixed distance in front of the test rig, allowing the cameras to be focused at the center of the tube in firing position. All indicator lights are visible to the researcher and all on/off switches are within easy reach. When a test run is to take place the cabin windows are closed and a curtain is drawn behind the cockpit, darkening the cabin for filming purposes.

The actual procedure during a test run consists of checking indicator lights to make sure the system is ready for testing, darkening the cabin, and then, when the desired g conditions have been attained, initiating the automatic sequencing by depressing the push-button sequencing switch. Following a test run the cabin may be illuminated and the tube carousel must be rotated to place and lock the next tube into the firing position. At this time adjustments may be made to prepare the system for another test cycle.

In the case of an emergency, an emergency operational checklist has been devised. The researcher's responsibility in this case is to shut down all system power by shutting off the master on/off switch - terminating the sequencing, and to inform the crew of the emergency situation.

III

RESULTS AND ANALYSIS

3.1 Lean Limit at Zero-Gravity for this Apparatus

Initially, the most important goal of this investigation was to determine a lean limit for methane-air mixtures in this apparatus at zero-g. Since this apparatus uses SFLT's, a limit found in it is a limit as defined by the U.S. Bureau of Mines (Coward and Jones, 1952).

In order to better understand the results obtained at zero-g, flame behavior at earth's gravity (one-g) in this apparatus was also investigated. In this way a comparison can be made between the zero-g and one-g behavior, and the effect of gravity on the lean limit can be examined. The one-g results are helpful in determining the influence that the apparatus has on the limits obtained, since data for one-g limit behavior can be found for several other experimental configurations.

Extensive laboratory tests were performed with this apparatus at one-g. The lean limit for methane-air mixtures in this apparatus for upward propagation at one-g was found to be 5.25% methane in air. This limit agrees well with the limit of 5.3% established by Levy (1965), and the limit obtained by Strehlow and Reuss (1980) of 5.27%. The agreement with the data of Strehlow and Reuss is significant since zero-g data from this experiment will be compared to the zero-g results obtained by Strehlow and Reuss.

The zero-g experimental data for this apparatus was obtained for mixtures ranging in composition from 5.7% methane to 5.05% methane.

This range was sufficient to allow the determination of the lean limit at zero-g. All flames in mixtures whose compositions were above the one-g limit (5.25%) propagated the length of the tube. Below the one-g upward limit, flames in mixtures as low as 5.10% propagated the length of the tube (see Table 1). From these results it is concluded that the lean limit for this apparatus at zero-g is 5.10% methane in air.

Accuracy in obtaining the zero-g lean limit in this experiment is insured by the experimental methods used. By observing entire flame histories, the extent of flame propagation can be determined exactly. In addition, the use of g-meters to measure acceleration in three orthogonal directions allows consideration of gravity distrubances in the determination of a flame's behavior. Finally, the use of SFLT's in this experiment allows the lean limit to be determined through a standardized method. More extensive testing, yielding more data for flames in mixtures of composition near 5.10%, would have been useful; however, the fact that the behavior of the flames is consistent in mixtures whose composition was less than 5.10% or greater than 5.11% indicate that the behavior was reproducible.

Table 1

Extent of Propagation Versus Composition
at Zero-Gravity

LEAN LIMIT AT ZERO GRAVITY

Percent Methane	Date	Propagation/Extinction
5.25*	7/31	Full Propagation
5.25*	8/1	Full Propagation
5.25*	8/1	Full Propagation
5.24	8/1	Full Propagation
5.22	8/2	Full Propagation
5.20	8/2	Full Propagation
5.20	9/13	Full Propagation
5.15	9/13	Full Propagation
5.11	9/13	Extinguished
5.10	9/14	Full Propagation
5.10	9/14	Extinguished
5.08	9/14	Extinguished
5.05	9/13	Extinguished

*5.25% Methane in Air is the one-gravity upward lean limit for this apparatus.

Comparison to the zero-g data of Strehlow and Reuss (1980) is somewhat difficult since their value for the lean limit depends on the assumption that unsteady motion would necessarily lead to extinction of the flame, and since their data includes mixtures whose compositions differ greatly from one to the next. Strehlow and Reuss observed a mixture of 5.22% supporting a steady flame which is assumed to propagate the full length of the tube, and a mixture of 5.10% supporting a flame of unsteady motion which is assumed to extinguish. With no data for mixtures with composition between 5.22% and 5.10%, the limit could be at any composition in the range from 5.10% to 5.22%.

Since apparatus dependence is of little importance in the comparison of Strehlow and Reuss' data and this experiment's data (the one-g limits differed by only .02%), the results can be compared easily. The lean limit of 5.10% obtained in this experiment agrees with the range of compositions which represent the lean limit in Strehlow and Reuss' experiment. Unfortunately, with only an estimate as to the exact lean limit for Strehlow and Reuss' configuration any more detailed comparison is impossible.

3.2 Behavior of the Lean Methane-Air Flame at Zero-Gravity

The lean methane-air flame propagating through an SFLT at zero-g exhibits behavior which could be described as a combination of the characteristics of upward propagating one-g flames and downward propagating one-g flames. For example, the zero-g flame may be described as a slightly flattened hemispherical flame cap with a relatively short flame skirt. This shape is similar to that of the one-g upward propagating flame which has a hemispherical flame cap and long flame skirt, while also having some of the characteristic flatness of the one-g downward propagating flame. In addition, the propagation speed of the zero-g flame is less than that of the one-g upward propagating flame and greater than that of the one-g downward propagating flame.

Propagation speeds for flames in this apparatus at zero-g have been determined from measurements taken from the filmed data for flames with compositions ranging from 5.7% methane to the lean limit of 5.1%. They are tabulated in Table 2, and plotted in Fig. 5 along with one-g upward data from this experiment, and zero-g and one-g upward data from the Strehlow and Reuss (1980) study. The plotted results emphasize the effect that the apparatus can have on flame behavior. The apparatus used in this experiment yielded slightly higher propagation speeds than the apparatus used by Strehlow and Reuss for both the case of zero-g and one-g upward propagation.

The zero-g propagation speeds tabulated and plotted here represent average propagation speeds taken over a flame's entire history. Propagation speeds were also calculated at every 1/24 second, by measuring the distance the flame propagated between frames. These "interval" speeds have been tabulated in Table 3 by listing maximum and minimum interval speeds, along with the average propagation speeds, for each flame. This fairly broad range of interval speeds for a given flame represents the effect of flame front oscillations on that flame's propagation, and while the range of interval speeds for a given flame

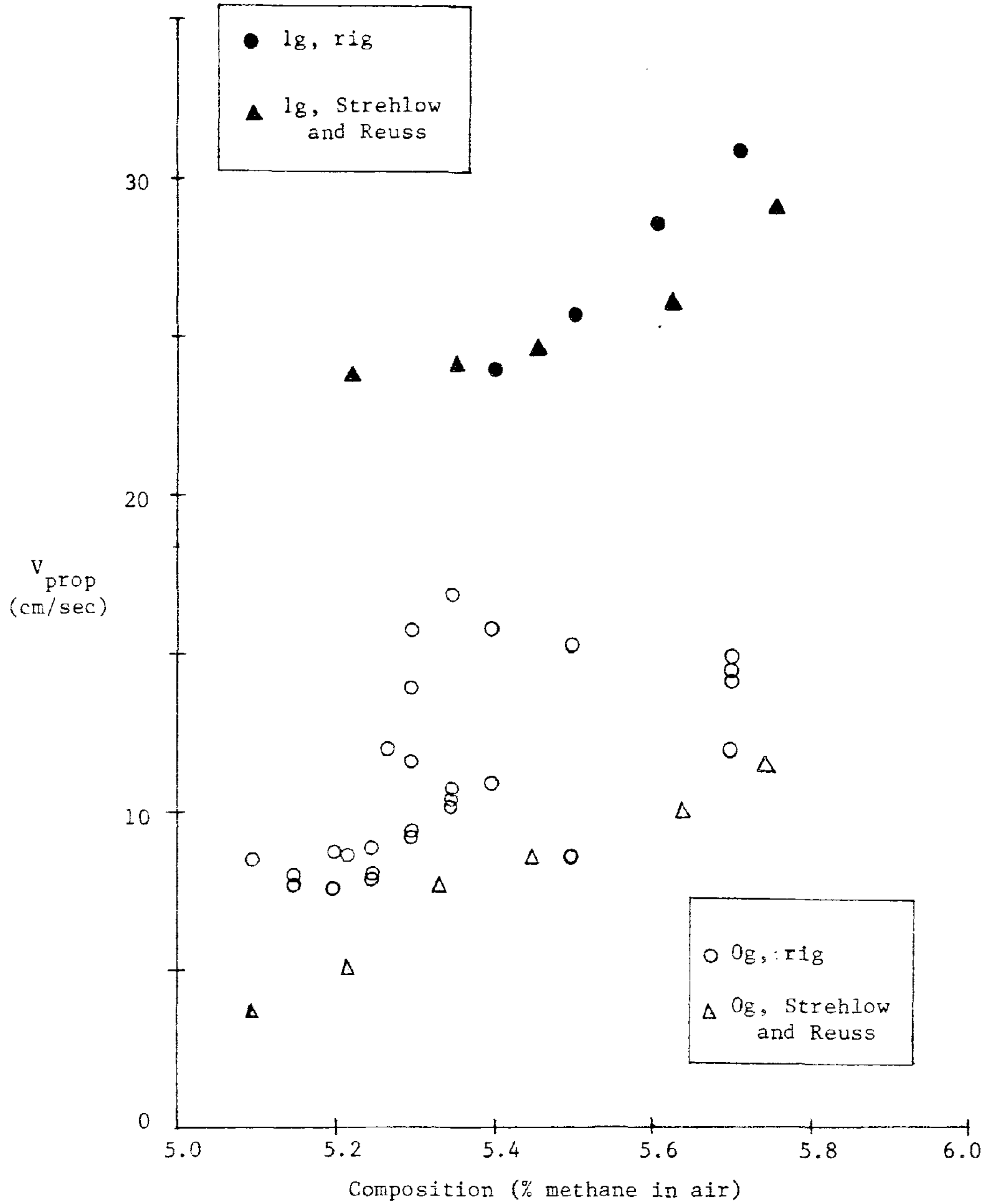

Fig. 5. Propagation speed vs. composition.

Table 2

Tip Propagation Speed Versus Mixture Composition

VELOCITY CHARACTERISTICS

Composition (% Methane)	Tip Speed (cm/sec)
5.70	14.77
5.70	14.00
5.70	14.34
5.70	11.81
5.50	15.14
5.50	8.43
5.40	10.79
5.40	15.62
5.35	10.06
5.35	10.22
5.35	10.51
5.35	16.73
5.33	13.80
5.30	9.16
5.30	11.49
5.30	15.62
5.30	9.24
5.27	11.89
5.25	7.81
5.25	7.98
5.25	8.79
5.24	7.72
5.22	8.63
5.20	7.39
5.20	8.69
5.15	7.87
5.15	7.72
5.10	8.40

Table 3

Minimum and Maximum Interval Propagation Speeds, as well as Average Propagation Speed, Versus Composition at Zero-Gravity

MAXIMUM AND MINIMUM INTERVAL SPEEDS

% Methane	$v_{i_{max}}$	$v_{i_{min}}$	v_{ave}
5.70	18.03	8.62	11.81
5.70	20.77	10.97	14.77
5.70	19.20	10.19	14.00
5.70	19.59	9.80	14.34
5.50	13.32	4.70	8.43
5.50	20.77	10.97	15.14
5.40	16.07	7.45	10.79
5.40	21.55	10.19	15.62
5.35	13.32	7.45	10.06
5.35	18.03	5.88	10.22
5.35	14.50	7.84	10.51
5.35	26.26	11.76	16.73
5.33	23.91	10.19	13.80
5.30	12.15	7.05	9.16
5.30	16.85	7.05	11.49
5.30	23.91	9.80	15.62
5.30	15.28	5.09	9.24
5.27	19.99	9.01	11.89
5.25	12.15	4.70	7.98
5.25	10.97	5.09	8.79
5.24	11.36	5.49	7.72
5.22	11.76	5.88	8.63
5.20	11.76	4.31	7.39
5.20	11.76	5.49	8.69
5.15	10.58	5.09	7.87
5.15	13.32	5.09	7.72
5.10	12.15	5.49	8.40

may be large, the average propagation speed for any single flame is usually consistent with the rest of the propagation speed data.

The burning velocity, or normal burning velocity, of a flame has a greater physical significance than the propagation speed, since the burning velocity is the velocity at which an adiabatic, strictly one-dimensional flat flame would propagate. Unfortunately, the burning velocities of the zero-g flames observed in this experiment were extremely difficult to analyze. This is due to their complex flame shapes and the fact that the 2-D images recorded on film may not properly represent the actual 3-D flame shape. Nevertheless, the burning velocities were calculated as accurately as possible. For a single flame, the burning velocities measured at different times in the flame's history were generally consistent. Unfortunately, the burning velocities were not as consistent from one flame to the next (see Table 4).

As mentioned earlier, the structure of the flames at zero-g possessed characteristics of both the one-g upward propagating and the one-g downward propagating flames whose shapes have been described by Strehlow (1984). While the zero-g flame had a cap-and-skirt shape similar to the one-g upward propagating flame, the cap was flatter and the skirt was shorter, similar to the nearly flat one-g downward propagating flame. In addition, the zero-g flame front often contained cells, a phenomenon exhibited by one-g downward propagating flames. This phenomenon was unexpected for the zero-g case and will be discussed in greater detail in a later section.

Table 4

Normal Burning Velocities for Flames at Zero-Gravity

NORMAL BURNING VELOCITIES

Composition (% methane)	Burning velocity (mm/sec)
5.70	47
5.70	46
5.70	51
5.70	49
5.50	35
5.50	29
5.35	39
5.35	24
5.35	43
5.35	45
5.25	26
5.25	33
5.25	35
5.15	36

A final characteristic of flame propagation at zero-g is the method of extinction. In this respect, the zero-g flame behaved somewhat like the one-g downward propagating flame. At zero-g, extinction begins with the flame skirt gradually shortening until only a flame cap remains. The flame cap then becomes flatter and slightly distorted. At this point the extinction process becomes rapid. This, along with the relative dimness of the flame makes the remainder of the extinction process difficult to observe. There seems to be a reduction in the diameter of this flat flame front just prior to the immediate extinction of the entire flame front. The behavior is similar to the extinction behavior of the one-g downward propagating flame as described by Jarosinski et al. (1982), but does not include the flame "rise" due to buoyancy that they observed just prior to extinction.

3.3 Cellular Instability

Cellular instability was observed in this experiment, in lean methane-air flames propagating at zero-g. While cellular structure is a common phenomenon in the one-g downward propagating flame, especially for very lean mixtures, its presence in the zero-g flame had not previously been observed or expected.

In these experiments, the cellular flame front has two or more distinct flame "cells" which varied in size and shape. These cells actually resemble individual flame fronts propagating side by side. Markstein (1964) postulated that these cells are caused by "selective-diffusion" of the deficient species in the mixture as influenced by flame curvature and flow conditions ahead of the flame. Recently, however, Sivashinsky (1983) has noted that cellular instability is really a thermodiffusive phenomenon associated with the presence of a deficient light species in the approach mixture. As Strehlow (1984) states, "when any sufficiently light species of the fuel-oxidizer pair is sufficiently deficient, any concave perturbation of a flat flame shape will grow to become a deep trough, because preferential diffusion of the light and deficient species toward the reaction zone will deplete that species in the neighborhood of the perturbation and cause the local burning velocity to be reduced." The flames which will be unstable to this process are those of a light fuel in a lean mixture or a heavy fuel in a rich mixture. Consequently, a lean mixture of methane, a light fuel, would be unstable to this type of perturbation.

Typically, the behavior of the cells observed in the zero-g flames of this study was similar to the cellular behavior reported by Markstein (1964) for flames in wide vertical tubes. In the zero-g flames which exhibited cellular instability, a trough would develop, separating the flame front into cells. The largest of these would propagate faster than the smaller cells, and would grow larger, eventually enveloping the smaller cells. This new flame front would then either propagate as a stable flame. or again break into cells repeating the process (see Fig. 6). In this manner, a cellular instability would often develop, die out, and appear again in the same flame. None of the propagating flames exhibited cellular instability throughout their entire history.

Cellular instabilities were observed at zero-g in flames over the entire range of mixture compositions tested, 5.70% to 5.10%. The probability of occurrence had no apparent dependence on the leanness of these lean mixtures (all flames in 5.70% mixtures exhibited cellular instability). The instabilities occurred throughout

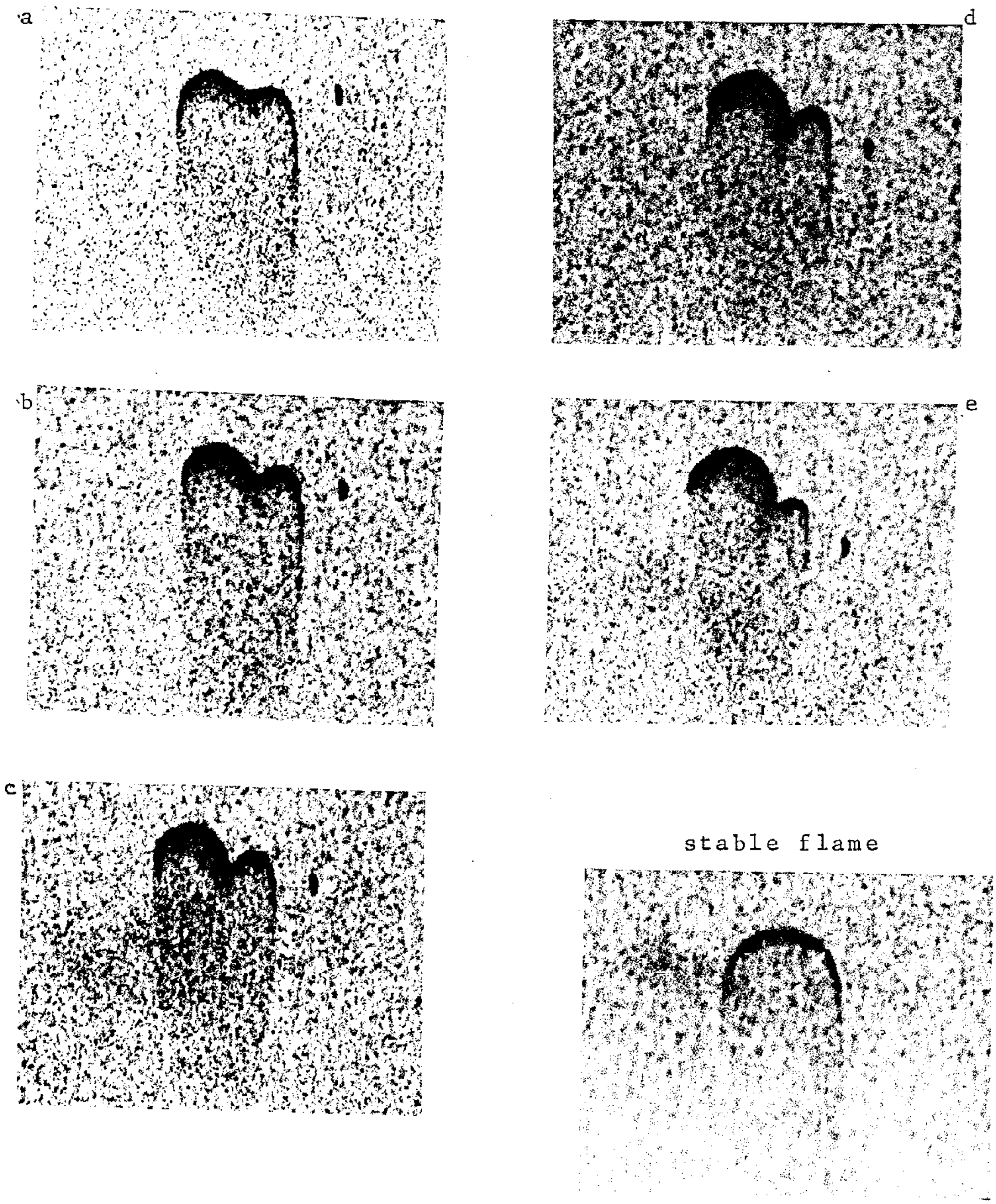

Fig. 6. Photographs of the development of a cellular instability. (time increases top to bottom, right to left) Note the stable flame for comparison.

the tube, and consequently cannot be attributed solely to the ignition process or to wall cooling effects. Additionally, small gravity fluctuations, or g-jitter had no noticeable effect on the occurrence of the instabilities. The flow field ahead of the flame could not be correlated with these effects since the cells appeared near both the tube center and the tube wall, and it was found that a flame could be well behaved before and after the instability appeared, with the overall burning speed unchanged by the occurrence of the instability.

As we have seen, cellular instabilities occur in flames propagating downward at one-g in lean limit mixtures, in flames in lean mixtures at zero-g and in flames propagating upward at one-g in wide vertical tubes. The first two flames have relatively slow burning velocities, while the third has a high burning velocity but a large surface area. Therefore the cellular instability may be related to the lifetime of an element of the flame. This is the time it takes for an element of the flame to propagate as a wave from the tip, the point at which the flame is held, to the end of the skirt. The relation between cellular instability and wave element lifetime would explain the occurrence of the instability in flames with low burning velocities in standard tubes, and in flames with higher burning velocities in tubes of large cross-section. In both cases, the longer lifetime of the flame element may be allowing the flames to become cellularly unstable.

3.4 Miscellaneous Gravity Loadings

In addition to the zero-g flame, two other methane-air flames were examined in this study. The first of these is the flame propagating downward while the gravity load is increased continuously from zero-g to one-g; this loading will be referred to as transitional gravity. Besides examining these two additional flames, the effect of g-jitter in the zero-g case will be discussed.

A two-g environment was obtained by flying the aircraft at a continuously increasing angle-of-attack. Unfortunately, the quality of these two-g trajectories was not as good as that of the zero-g trajectories. Consequently, the amount of useable data at two-g was very small. Nonetheless, the useable data was consistent and it yielded some general observations relative to the behavior of two-g upward propagating flames.

A methane-air flame propagating upward at two-g is a stable flame which exhibits a significantly higher propagation speed than the one-g upward propagating flame. These propagation speeds ranged from 34.4 cm/sec to 37.4 cm/sec for the two mixture compositions tested, 5.35% and 5.55%. These speeds are approximately 10 cm/sec higher than those of the stable one-g upward propagating flame of similar composition and approximately 22 cm/sec higher than the average propagation speed of all zero-g flames of similar composition. The two-g upward propagating flame also had a longer flame skirt than the one-g upward propagating flame; this behavior is predictable given the relation between propagation speed and flame skirt length as proposed by Strehlow (1984).

Another flame which was studied is the flame which is ignited at zero-g and which propagates while a continuous gravity loading is applied. This transitional gravity environment was obtained when part of a Keplerian trajectory was modified. The gravity loading for each trajectory was recorded on film, allowing the individual trajectories to be different while still yielding valuable results.

A particularly interesting example of a flame in this environment is the downward propagating flame whose mixture composition is between the zero-g lean limit of 5.10% and the one-g downward lean limit of 5.85%. This flame, ignited at zero-g, will begin propagation in the zero-g environment, and as it propagates, the gravity load is increased. At some point, the flame will be too lean to propagate downward at the given gravity, and the flame will extinguish.

Flames in mixtures with compositions greater than the one-g downward limit of 5.85%, did not extinguish with the gravity loads applied. For mixtures of less than 5.85% methane, extinction occurred at moderately low gravities for all flames (see Table 5). Considering the fact that the mechanisms causing extinguishment may have been initiated at a lower gravity load than that which was recorded at extinction, the gravity loads which cause extinction in these flames may actually be lower than those recorded and tabulated. Nevertheless, the loads recorded at extinction are less than one-half-g for all flames, including a flame in a 5.80% mixture. For mixtures nearer the zero-g lean limit, extinguishment occurred at gravity loads as low as one-tenth-g.

The method of extinction for a flame propagating downward in transitional gravity is very similar to that of the one-g downward propagating flame as described by Jarosinski et al. (1982). In our case, as gravity loading was increased the flame flattened to a disk-shaped flame front which would propagate with low frequency oscillations at a gradually decreasing speed. Just prior to extinction, the disk-shaped flame would slow markedly, its diameter decreasing, until the small disk of flame would extinguish completely (see Fig. 7).

Table 5

Gravity Loads at Extinction for Flames in Transitional Gravity

Composition (% Methane)	Gravity at Extinction
6.10	No Extinction
5.90	No Extinction
5.80	0.43 - g
5.40	0.43 - g
5.40	0.30 - g
5.30	0.10 - g

a d

b e

c f

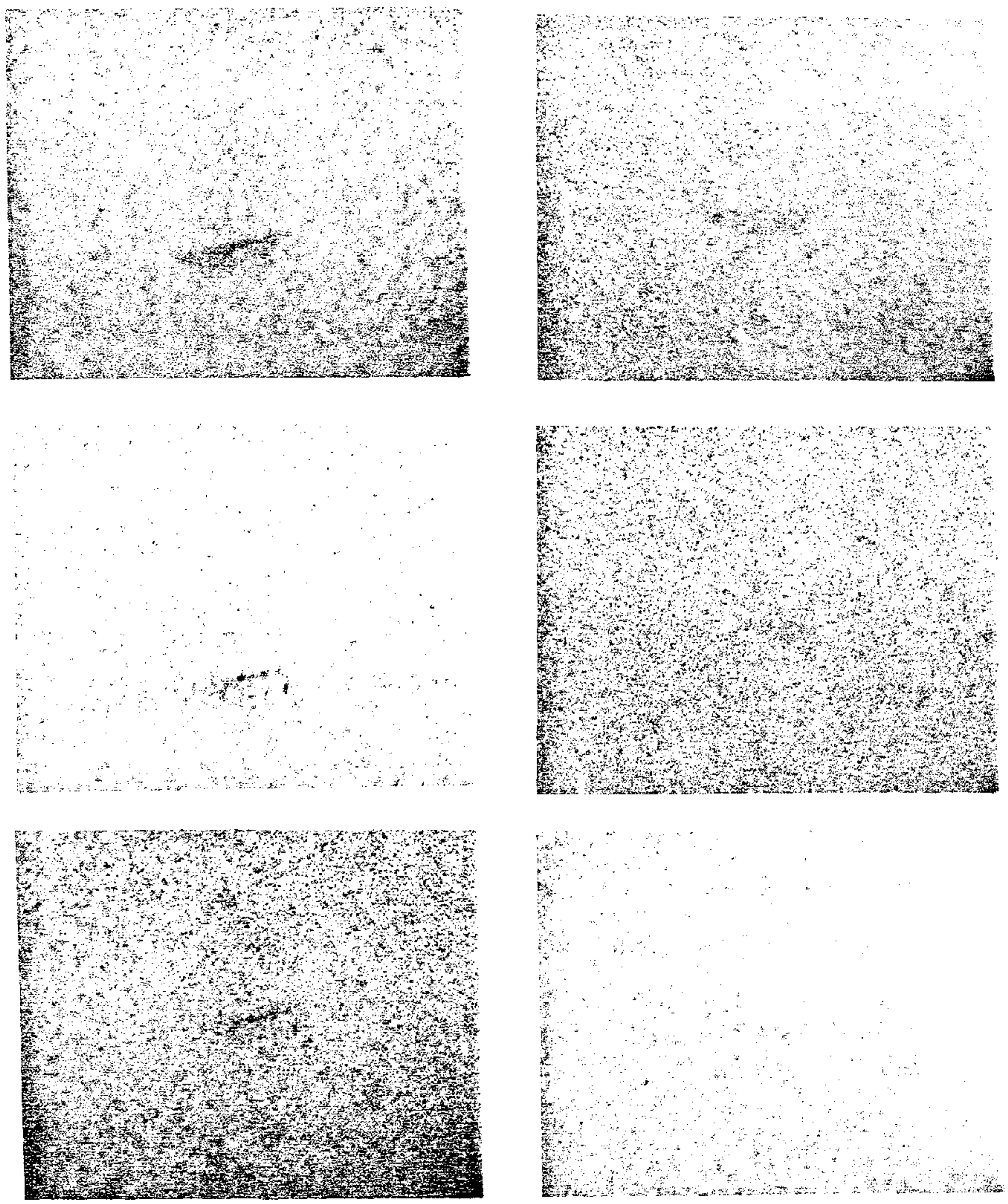

Fig. 7. Photographs of a flame extinguishing under a transitional gravity load. (time increasing top to bottom, right to left)

The availability of gravity measurements at all times during a flame's propagation allows an examination of the effect of g-jitter, small gravity fluctuations, on the flame behavior. These gravity fluctuations are the inevitable result of obtaining zero-g through flight.

The effect of g-jitter on propagation speed is minimal. For a typical flame, a slight change in gravity may be followed by a large change in speed, while a large change in gravity may be followed by a small change in speed, and occasionally a change in gravity would not produce any change in speed. Moreover, the time lapse between a change in gravity and the change in speed was inconsistent in those cases where correlations were attempted. This leads one to the conclusion that g-jitter had little effect on a flame's propagation speed.

Another consideration of the effect of g-jitter on flame behavior is the relation between g-jitter and cellular instability. As was mentioned earlier, g-jitter had little noticeable effect on the occurrence of cells, since cellular instabilities appeared in even fifteen-thousandths of a g. Thus it appears that g-jitter has little appreciable and reproducible effect on the behavior of the lean methane-air flame at zero-g. This is true for both flame shape and flame speed.

In the case of g-jitter, the gravity loads range approximately from plus four-hundredths of a g to minus four-hundredths of a g. These loads have no appreciable effect on the behavior of lean methane-air flames. Conversely, in the case of transitional gravity, a gravity load of one-tenth of a g may cause extinction of a flame in a near limit methane-air flame. These results could indicate the presence of a critical gravity, below which the effects may be neglected and above which the effects are similar to that of the one-g environment. More extensive testing is needed, however, to allow prediction of a critical gravity for extinction.

IV

CONCLUSIONS

For this study of lean limit methane-air flames at zero-gravity, a new facility, the NASA Lewis Research Center Airborne Research Laboratory, was used, and an experimental apparatus was designed and constructed specifically for use in this facility. The quality of the results indicates that the facility provided an excellent test environment for a number of test configurations, and that the apparatus was well designed for use in the facility.

In this study the behavior of lean limit methane-air flames at zero-g was investigated. Several goals were accomplished. A lean limit for methane in air at zero-g was obtained. Flame structure, flame speed, and the extinction process were observed for the zero-g flame. Cellular instabilities in the zero-g flame were observed and investigated. Finally, the effects of three distinct gravity loadings on the lean methane-air flame were examined.

The initial goal of this study was to determine a lean limit for methane in air at zero-g. A standardized method, utilizing standard flammability limit tubes, was used to obtain the limit, which was found to be 5.10%. This value for the lean limit agrees with the value obtained in a previous, less comprehensive experiment.

The behavior of the lean methane-air flame at zero-g was markedly similar to the behavior of a lean methane-air flame propagating downward at one-g. The zero-g flame exhibited some of the characteristic flatness of the one-g downward propagating flame, and had a similar propagation speed to the one-g downward propagating flame. More significantly, however, the zero-g flame extinguished by a mechanism similar to that which causes extinction in the one-g downward propagating flame; specifically, the limit flame at zero-g is drastically affected by heat loss to the tube walls. Additionally, cellular instabilities occurred in the zero-g flame. While frequently observed in the one-g downward propagating flame, cellular instability had not previously been reported in zero-g flames. Occurrence of these instabilities was shown to be independent of the ignition process, g-jitter, and, within the range tested, mixture composition. Since the lean methane-air system is known to be cellularly unstable except in special cases, some evidence was presented to support the possibility that the cellular instability may be related to the lifetime of a flame element.

The behavior of the lean methane-air flame was also examined for three additional gravity loadings, including a two-g loading, the random loading of g-jitter, and a transitional gravity loading from zero-g to one-g. The two-g flame is a stable flame exhibiting a high propagation speed. The effect of small gravity fluctuations, or g-jitter, on all the flames tested was found to be negligible. These gravity loads were in the range of plus/minus four-hundredths of a g. The flames propagating downward in the transitional loading from zero-g to one-g were particularly interesting. In mixtures with compositions below the one-g downward limit, all flames extinguished at relatively low gravity loads - below one half g for all extinguishing mixtures, and as low as one-tenth of a g for one mixture whose composition was near the lean limit. The extinction behavior of flames in transitional gravity was very similar to the extinction behavior of a one-g downward propagating flame.

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